Extended Range Underwater Optical Imaging Architecture

F. R. Dalgleish[1], F. M. Caimi[1], C. H. Mazel[2] and J. M. Glynn[2]

[1]Harbor Branch Oceanographic Institute
Fort Pierce, FL 34946 USA

[2]Physical Sciences Inc.
Andover, MA 01810 USA

***Abstract* - Synchronous scan imagers have demonstrated improved ability to see underwater allowing operation at up to 6 optical attenuation lengths. Recent developments in laser and scanning systems show promise for further miniaturization of these systems to allow operation from small AUVs. This paper describes an approach that exhibits several advantages compared to larger systems having a similar receive aperture and Field of View (FOV).**

I. Introduction

For the increasing and diverse applications of the autonomous underwater vehicle (AUV), the ability to produce high resolution images of the targets or survey site under investigation is critical. Depending on the size and complexity of the target, optics can be the only sensing modality to make this possible. In the exploration of unknown or dynamic environments, rapid topographical seabed variations can occur at rates greater than the vertical axis performance of the AUV, and it is essential that the AUV is programmed to fly at an extended range above the seabed in order to avoid potentially catastrophic bottom collisions. This requires a particular type of optimal underwater optical imager.

Research into optimal underwater optical imaging has been approached through both simulation and experimentation over the last three decades. Computer models have been developed [1][2] which show that synchronous scanning imagers (also known as volume scanning or laser line scan) may become contrast limited between 5 – 7 attenuation lengths, the limiting factor being forward scattered light. This has been further investigated through a series of tank and field deployments of several such systems [3][4][5]6][7][8][9]. Jaffe [1] also showed through simulation that range-gated imagers could perhaps perform at up to 7 attenuation lengths, ultimately being power (or photon-) limited due to the exponential decay of light through water. Indeed, several range-gating prototypes, either staring or non-synchronous scanning laser-radar models have been built and tested over recent years [10][11][12][13][14][15][16].

The main operational issues with both classes of imager in the dynamic environment (with persistent variations in platform altitude, attitude and the optical properties of water) is their small depth of field (DOF) which can lead to frequent image drop-out. In the case of the synchronous scanning imager, the DOF is determined by the source-receiver separation, distance to the target and the beam divergence and acceptance angle of the source and receiver, respectively. In practice, the along track axis of the receiver aperture is widened for acceptable performance, or fine adjustment of the focal distance is made possible via steering mirrors which are slaved from an onboard altimeter. For the range-gated imager, variations in distance to the target result in a change in the required delay time after which the receiver should be gated to acquire the photons returning from the seabed. Other than these dynamic considerations, the size, weight and power requirements are also highly relevant when designing such a system to be deployed from an AUV.

Our approach here is the design of a more compact synchronous scanning architecture. Although utilizing a reduction in separation between the source and receiver, which can lead to increased noise from near-field back scattering events when using a continuous wave laser and 'open' receiver, the design allows a greater optical synchronicity and hence allows a narrower receiver acceptance angle than its larger predecessors, whilst still achieving a 70° scan angle. By employing a lateral separation between the transmit and receive channels, the system has greater immunity to platform pitching which is experienced by an AUV when being controlled by an altitude autopilot. Another interesting attribute of this novel scanner design is that it virtually eliminates the undesirable effect known as beam walk-off which occurs with some scanner design as the scan traverses its full angular range. This allows a narrow aperture photodetector to be used to receive the target signal which typically has a faster response and exhibits lower noise than their larger counterparts.

The testing of extended range optical imagers under highly controlled conditions is an equally important capability for both system performance evaluation and validation of image prediction models. The Center for Ocean Exploration at Harbor Branch Oceanographic Institution has recently completed an extended range ocean optics testing facility

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14. ABSTRACT

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which allows rigorous testing of both classes of imager up to a stand-off distance of 13 m whilst precisely controlling the optical properties and ambient light levels.

This paper will further describe the systems concept for the AUV-based imager, scanner performance requirements, and optical simulations of the system and scanner. Additional system evolution is planned over the next year.

II. SYSTEMS CONCEPT

A. Performance Requirements

The image resolution that synchronous scanning systems can achieve is largely determined by the laser spot size at the target and the precision with which the receiver can track this spot throughout the entire scan angle. The minimization of this instantaneous field of view (IFOV) also reduces the undesirable scattering volume which ultimately limits the imaging range of the system.

In the enhanced scenario where precise control of the temporal aspects of both source and receive channels is implemented or potentially a modulated signal is superimposed on the laser pulse, this scanner has been specifically designed to allow use of a small aperture photodetector, without compromise to the maximum scan angle achievable. Such a small aperture photodetector exhibits lower noise levels and can achieve a higher bandwidth than the larger aperture receivers required by the previous systems. Furthermore, this apparatus has been specifically designed to fit inside a common form factor 21” diameter autonomous underwater vehicle (AUV). A summary of the performance requirements of both the scanner and its implementation as an imaging payload is shown below:

- 70° cross axis scan angle
- High degree of optical synchronicity over the entire scan angle, requiring an IFOV slightly larger than the laser spot at distance through turbid water, therefore a minimal common volume
- Similar effective collection aperture than previous systems (~20cm^2)
- Small or negligible amount of ‘walk’ over the photosensitive region of the receiver
- Mechanism to finely and rapidly adjust the focal distance
- Cross axis pixel resolution of less than 0.5 cm at 10 meters altitude
- Entire package can fit in a 21” diameter cylindrical payload section
- Power requirement (less than 200W)
- Low cost (less than $200,000 per imager payload)

B. Scanner Description

The scanning architecture is built around a single six-faceted polygonal scan mirror. The objective is to have a very narrow IFOV at the receiver channel which is optically coincident with the outgoing laser pulse throughout the entire scan angle for a fixed stand-off distance. As the stand-off distance is adjusted, a mechanism to maintain this optical synchronization is required. The incorporation of two symmetrical steering mirror assemblies allows this to be accomplished. Indeed, it is this symmetry of the source and receiver channels about the center axis of the polygon, which significantly reduces the detector photocathode area required to complete a full scan through 70º. Figures 1 and 2 show the basic scanner concept. For the AUV-deployed scenario, there is an additional folding mirror at the edge of both channels (not shown) which are used to fold the transmit and receive optical paths back along the longitudinal axis of the hull.

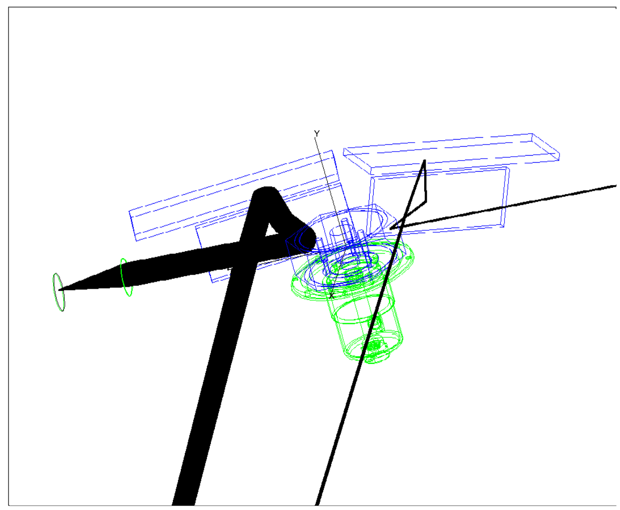

Figure 1. Scanner concept illustrating rotating polygon scanner, steering mirrors and beam exit to small aperture detector.

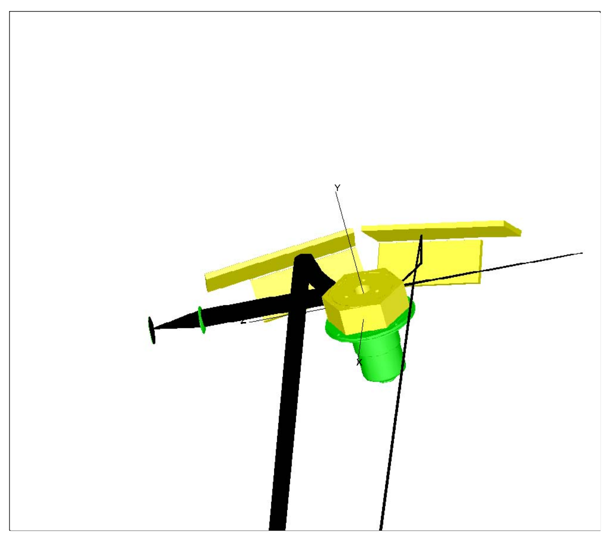

Figure 2. Solid Model of previous figure.

C. Transmit Optics

The Model 58-GLS-309 is a low noise hermetically sealed diode-pumped solid state Nd:YAG continuous wave laser manufactured by Melles-Griot. It has an adjustable output power, with a maximum of 3W at 532nm. When used with a collimator, the beam diameter is < 2 mm with a far-field beam divergence of < 2 mrad.

The laser output is folded by 90° along the beam entry axis towards the polygon, where it is deflected via the transmit steering mirror pair over the top of the polygon and through the optical port into the water (figure 1 and figure 2).

D. Receive Optics

The returning photons entering the optical port from the target are incident on the upper receive steering mirror, where they are deflected to the lower receiver steering mirror and onto the other side of the polygon, where the light is directed towards a 90° folding mirror and into the back-end receive optical path. This consists of a condensing lens, a 2-axis aperture stop (positioned at the focal point of the lens) and the photomultiplier tube (PMT) which may include an input bandpass filter. The instantaneous field of view (IFOV) is determined by the relationship of the condensing lens focal length f_l to the aperture stop dimension r (not shown).

$$IFOV \cong \quad a\tan\left(r/f_l\right) \qquad (1)$$

E. Computing and Electronic Architectures

The photons that return from the target hit the photocathode of the PMT producing electrons, which are multiplied in the dynodes creating an output current.

The signal that comes out of the PMT is then filtered and amplified to use more of the dynamic range of the decimator that produces 12-bit values. A FIFO stores these values while it waits for the data to be requested by the digital signal processor (DSP), which passes it to the PC running the graphical user interface (GUI), which displays a waterfall image and/or stores it to file. The GUI also has a 'digital zoom' feature which allows the user to select an angular range over which to acquire the return signal with a cross axis pixel resolution of up to 4000. Limited by ADC sample rates and DSP clock speed, the highest resolution setting possible with the current DSP and control board is 4000 pixels within a 12° angular range.

For smaller dimensions and lower power consumption the PC-104+ form factor has been used. It had been determined from previous work at Harbor Branch [17] that burst data transfer using the direct memory access (DMA) allows for optimal performance. A Pentium III/1GHz processor with the PC-104+ form factor is used as the interface between the system and the user. Through its PCI bus, a DSP (SPM186420ER1000) with the capability of doing 8000 MIPS processes and passes the information acquired from the PMT.

The DSP also has control over the speed of the polygon, gain of the amplifier, analog to digital sampling rate, additional input/output (I/O) lines, and digital to analog (DAC) outputs. The system block diagram of the prototype synchronous scanning imager is shown in figure 3.

To synchronize the start of line to the acquisition process, a small silicon photodetector (PDU-V100) is hit by the laser just before the laser exits the port, triggering an interrupt that starts the data acquisition process.

The total power requirements of the prototype are listed on the bottom right of figure 3.

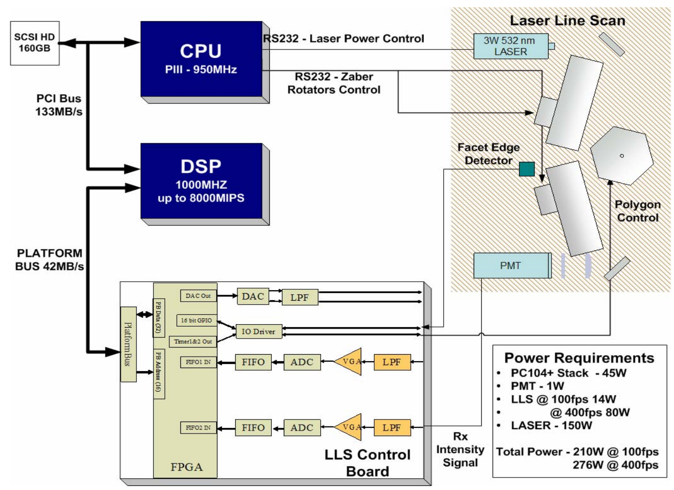

Figure 3. Synchronous scan imager block diagram.

III. MODELLING AND SIMULATION

Ray trace modeling with TracePro™ was used to design the scanner optics and to determine system performance when operated in realistic conditions. These include the inclusion of an optical window for tank testing, the divergence of the laser source, realistic reflectivity values for each surface in the scan, and complex valued refractive indices for a water medium.

The most common design of existing synchronous scanner [4][5][6][7][8] uses dual 45 degree pyramidal polygons with 5 facets on each. An undesirable issue with this configuration is that both the output scan field and the receive scan field are curved, but in the opposite directions. This causes the system to require a larger receive IFOV than desired and produces an arc across the face of the detector from the returned laser light during the scan. This effect can be shown by ray tracing the previous used geometric configurations. The system of figures 1 and 2 however was shown to trace out a much smaller ray bundle on the detector when scanned over a 70° total scan angle. To illustrate this behavior the geometry of figure 4 is used but the polygon is rotated by roughly a quarter of a facet. Figure 5 illustrates a +14° scan through a flat port used in tank testing the concept.

In an AUV application, a cylindrically shaped port may be used to allow the full 70° scan angle to be achieved cross track to the AUV travel direction. Ray trace results for this geometry were used to estimate the ray bundle position deviation on the detector face. Using a planar target, the required aperture stop for the entire 70° scan was a slit 2.5 mm by 0.5 mm. This corresponds to 25 mrad along the scan axis (which also determines the DOF) by 5 mrad normal to the scan axis. The deviation on the detector face over the entire scan was less than 2 mm.

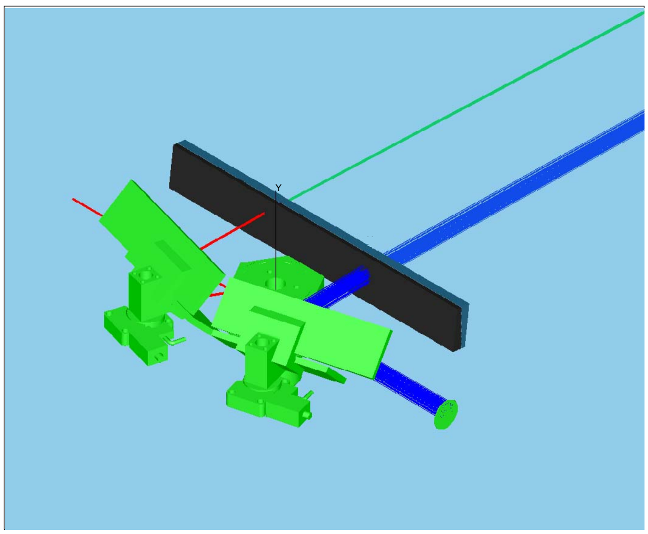

Figure 4. Ray trace showing laser (left) and return beam (right) using a flat optical port.

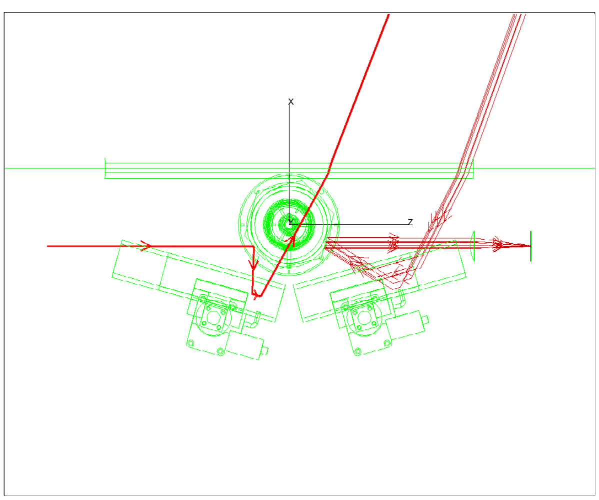

Figure 5. Example of ray geometry using a flat optical viewport and illustrating the effect of a +14° scan on the detector ray bundle position.

The ray trace simulations also allow estimation of the captured flux at the target in relation to the laser output. Assuming a distance of 12 meters to target with surface reflectivity 20%, a 2 W laser, and clearest water, the received optical flux is in the 10^{-6} watts range. This combined with accurate modeling of the scattering properties of coastal water can provide information needed for design of the detector electronics (i.e. PMT responsivity, gain, amplifier etc.) for at-sea operation.

F. *Monte Carlo Models*

Though TracePro™ uses a Monte Carlo ray trace technique with an importance sampling feature, the time consumed in modeling scattering from realistic water conditions becomes excessive when a large number of rays is desired. Consequently, we have used simulation software developed by Metron (Reston, VA) for both performance prediction of continuous wave excitation [1] and for pulsed excitation [19] where time history plots are also required. The ongoing testing of the prototype imagers will also serve to validate these codes.

IV. EXPERIMENTATION

G. *HBOI extended range ocean optics test facility*

HBOI is also developing a unique extended range underwater optical test facility, where inherent optical properties (IOPs) and ambient lighting levels can be precisely controlled. The underwater facility (13 m by 7 m by 2 m) will allow 70° FOV imaging in the horizontal axis for stand-off distances up to 7 m, with almost 50° FOV possible up to 13 m.

The facility includes a moving seabed simulator, creating the effect of the imaging system being flown over the seabed at a precisely controlled altitude at velocities that would be typically experienced when deployed from an AUV (up to 5 knots). The feedback for both rotational speed of the target and its stand-off distance is provided by a 500 KHz pencil beam sonar.

There is a fixed catwalk which runs the entire length of the tank on one side and a moveable catwalk which spans the minor axis of the tank and allows targets or instruments (rated at 500 lbs max) to be deployed over the distance of the major axis with the effective stand-off distance from the port being adjustable from 0.25 – 13 m. Figure 6 shows the facility in use.

For use with the facility are AC-9 and C-Star transmissometers from Wetlabs. As well as a pure water calibration station for these instruments, there is a 3 axis rolling deployment carriage for each of the instruments (and indeed for any instrument weighing less than 200 lbs) allowing 3-D sampling of the entire water volume.

At one end of the tank where there are two optical ports, a 4 meter x 2.5 m x 2.5 m mobile optical lab has been built, which is equipped with a/c and laminar flow box/HEPA filtering (i.e. a clean room). Within this there is a two layer mobile optical breadboard.

The surface of the tank has a 99.8% efficient light cover made from 63,000 black spheres (planned to be operational in September 2006).

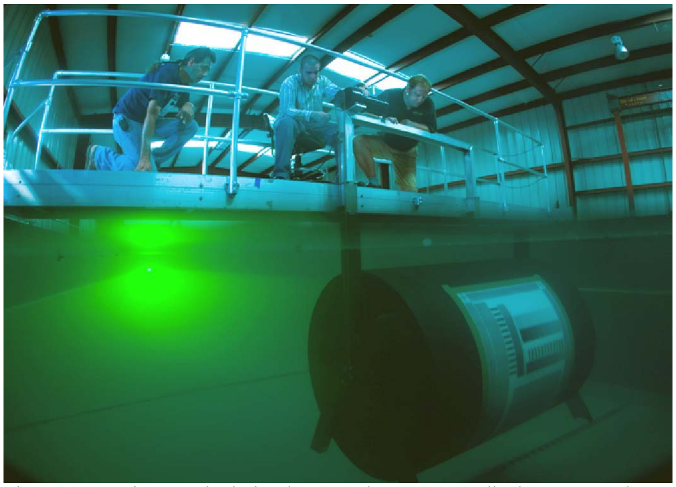

Figure 6. Rotating "Seabed Simulator" and access catwalk above test tank.

V. CONCLUSIONS AND FUTURE WORK

The overall objective of this research is to develop a compact synchronous scanning system which is suitable for deployment as an imaging payload onboard the 21" diameter AUV or smaller. The modeling and simulation activities performed herein have shown great promise for the novel single polygon scanning architecture which would form the basis of the proposed system. At present, experimentation with a continuous wave laser is being performed, and the results will be delivered in the conference presentation portion of this paper. However, the performance of the scanner with a pulsed laser and gated receiver is expected to further improve viewable range by reducing background noise from near field back scatter as well as ambient light. This has been investigated through simulation [18] [19].

Over the last year our industrial collaborators have been developing and packaging a novel pulsed green laser with the required energy per pulse, pulse duration and pulse repetition rate to demonstrate the utility of time-gated synchronous scanning. Perhaps the most important attribute of this scanner towards making this prototype demonstrator successful is the high degree of optical synchronicity throughout the entire scan angle whilst being compatible with a small, fast photodetector.

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